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DETERMINATION OF THE RESPONSE OF COATED FABRICS UNDER BIAXIAL STRESS: COMPARISON BETWEEN DIFFERENT TEST PROCEDURES

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Key words: PVC coated polyester fabric, biaxial test procedures.

Summary. The biaxial response of a PVC-coated polyester fabric is investigated using three different test procedures. The influence of the test procedure on the experimental data is discussed. A new approach based on a response domain is proposed.

1 INTRODUCTION

The estimation of the biaxial mechanical behaviour of coated fabrics is crucial for the design of tensile structures. This design relies on advanced softwares (form-finding, cutting pattern generation, stress determination) that require accurate material data. The material properties obtained from the biaxial tests strongly depend on both the test protocol that generates the stress-strain response and the post-processing of these experimental data. However, there is no standard method for biaxial tests in Europe so far. Therefore most laboratories develop their own protocol based on their experience, resulting in significant differences between the test data to process. Moreover, it has been shown that the post-processing has a major influence on the material parameters[1].

In this paper, the influence of the biaxial test procedure on the stress-strain response of a PVC-coated polyester fabric is investigated by comparing different methods:

- the standard of the membrane structures association of Japan (MSAJ)[2];
- the test method proposed by Bridgens *et al.* that tries to reproduce the *in situ* material behaviour with a pre-stressing, a conditioning and a radial load history[3]; this method is thereafter mentioned as the NCL method, in reference to the Newcastle University;
- the protocols currently used at EMPA.

2 EXPERIMENTAL SETUP

For each test procedure a cruciform specimen made of Valmex 7318 PVC-coated polyester fabric was tested on our biaxial test machine[4] (Figure 1). The material has a weight of 1000 g/m^2 and a tensile strength of 60 kN/m. The central square of the specimens is 500 mm wide. Each cruciform arm is made of five strips which are independently loaded by an electromechanical drive mounted on linear bearings. Tests are load-controlled by the use of 10 kN load cells fixed between every pair of drive and grip. Strains are measured by the use of two needle-extensometers. Tests are performed in a climatic room ensuring a constant temperature of 22°C.

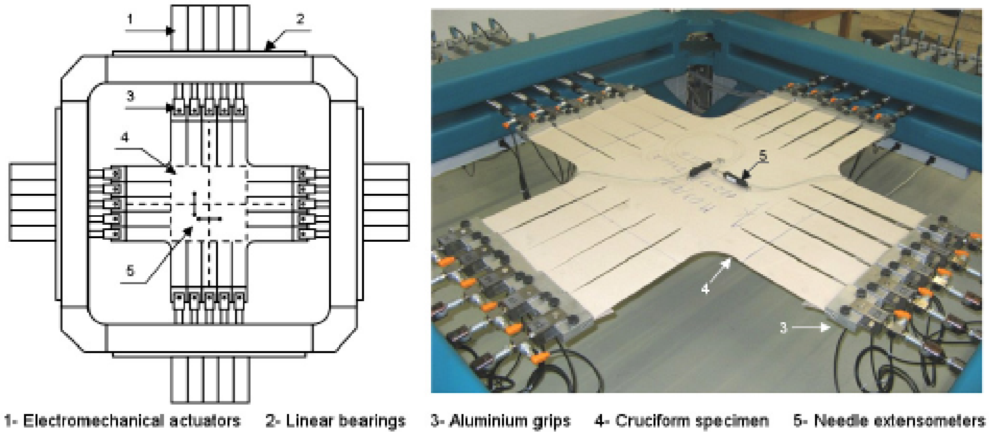

Figure 1: Biaxial test machine

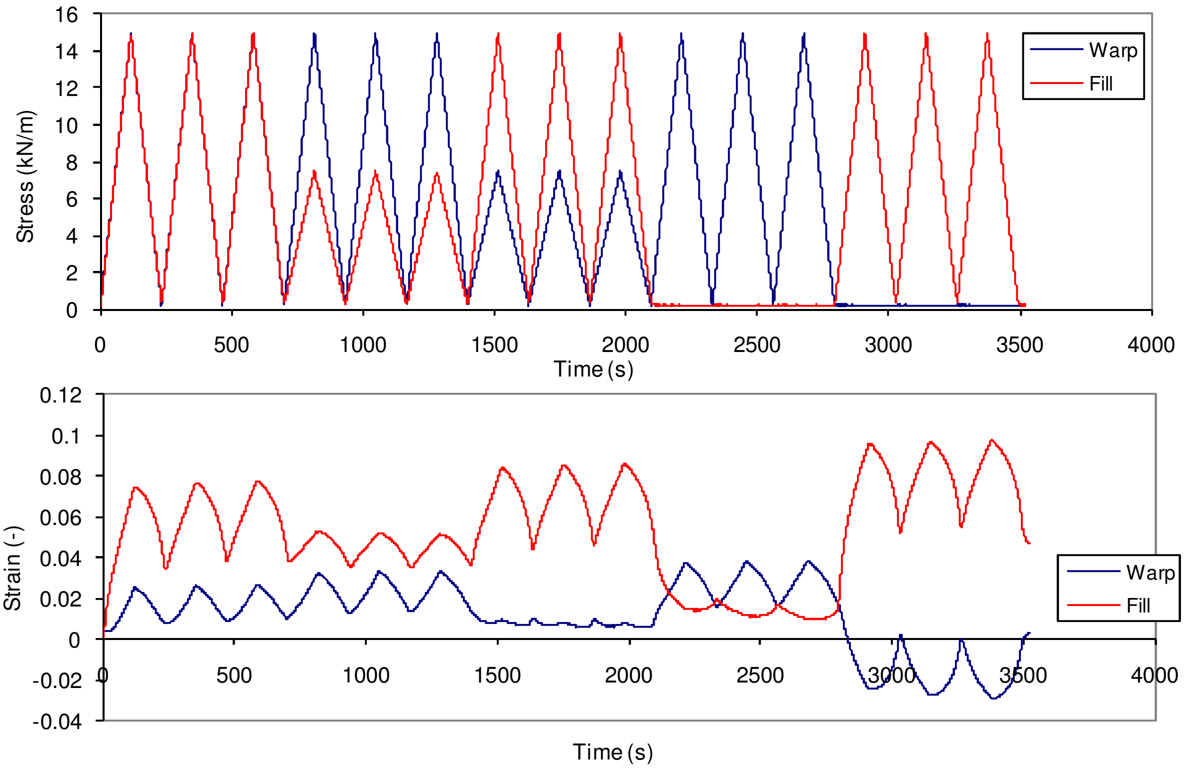

Figure 2: MSAJ test protocol: load history and corresponding strain measurement

3 TEST PROTOCOLS

3.1 Standard of the Membrane Structures Association of Japan (MSAJ)

The standard of the Membrane Structures Association of Japan[2] is the only existing standard for the biaxial testing of coated fabrics so far. This standard allows some flexibility for the sample geometry and test conditions, so that it is applicable to most biaxial machines. The load profile explores various load ratios with repeated load cycles in order to remove residual strains (Figure 2). The maximum test load is set to 25% of the UTS (Ultimate Tensile Strength). The load is supposed to reach 0 between every load cycle (no pre-stress). However, this condition is not possible to achieve with our biaxial machine. Since the actuators are load-controlled, due to the free movement of all 20 actuators, a pre-stress equal to 0 N can lead to an undesired displacement of the sample in the machine. Therefore a very low pre-stress equal to 0.2 kN/m was applied (0.3% of the UTS). For each load ratio, namely 1:1, 2:1, 1:2, 1:0 and 0:1, three load cycles must be applied. For a material characterization at least 3 specimens must be tested, while for our comparative study only one specimen was used.

The determination of the material elastic constants from the experimental results is not described in the standard. As a result it is possible to obtain different material properties depending on result interpretation[1].

3.2 Test protocol proposed by Bridgens *et al.* (NCL)

Bridgens *et al.* recently developed a test protocol with the aim of simulating the normal load condition of an *in situ* fabric[3]. The test protocol consists of three stages (Figure 3):

- pre-stressing: a pre-stress is applied for approximately 17 hours in order to avoid high initial levels of creep;
- conditioning: the fabric is subjected to loads that are 10% higher than the design load in order to simulate the behaviour of a fabric which has been exposed to environmental loads;
- test: radial load paths are applied that explore the fabric response above and below pre-stress in an order that aims at limiting the influence of the recent load history.

During the test, the sample is loaded up to 20% of the UTS, which is a typical value to avoid tear propagation in the material. The pre-stress is set to 1.3% of the UTS.

It is expected that after the pre-stressing and the conditioning the material has reached the typical behaviour of an *in situ* fabric, with few level of creep. The remaining residual strains are removed from the experimental data under the assumption that the greater the applied load the greater the rate of creep[3].

After removal of the residual strains, the *in situ* biaxial stress-strain behaviour of the fabric is obtained for each load cycle A to H.

Based on the test data, Bridgens proposed a new approach that uses 3D response surfaces[5] in order to allow a better representation of the material non-linear behaviour.

3.3 Test protocol used at EMPA

The protocol used at EMPA is based on the recommendations of the European Design Guide for Tensile Structures[6], which leads to a similar test to the one described by the Japanese standard. Different load ratios are explored with 5 load cycles each time. The maximum test stress and the pre-stress are set to 20% and 4% of the UTS, respectively. The pre-stress is applied prior to loading and maintained during 2 minutes. The material is also kept at pre-stress level for 2 minutes at every change of load ratio.

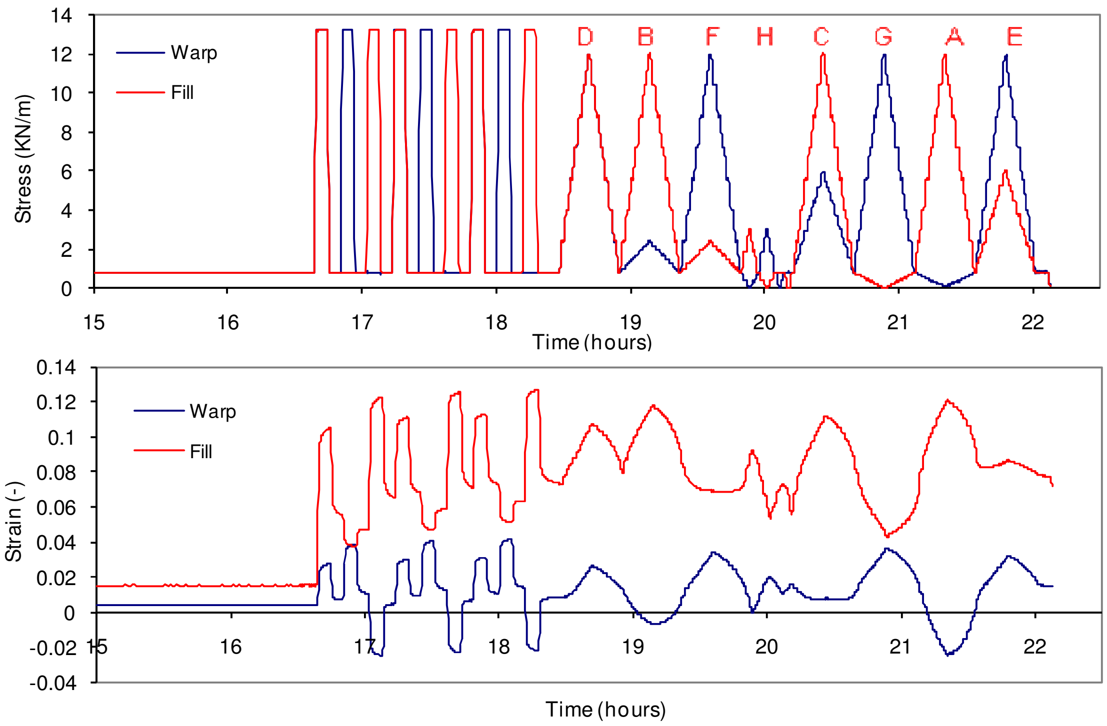

Figure 3: Load history and corresponding strain measurement for the two last phases of NCL test protocol

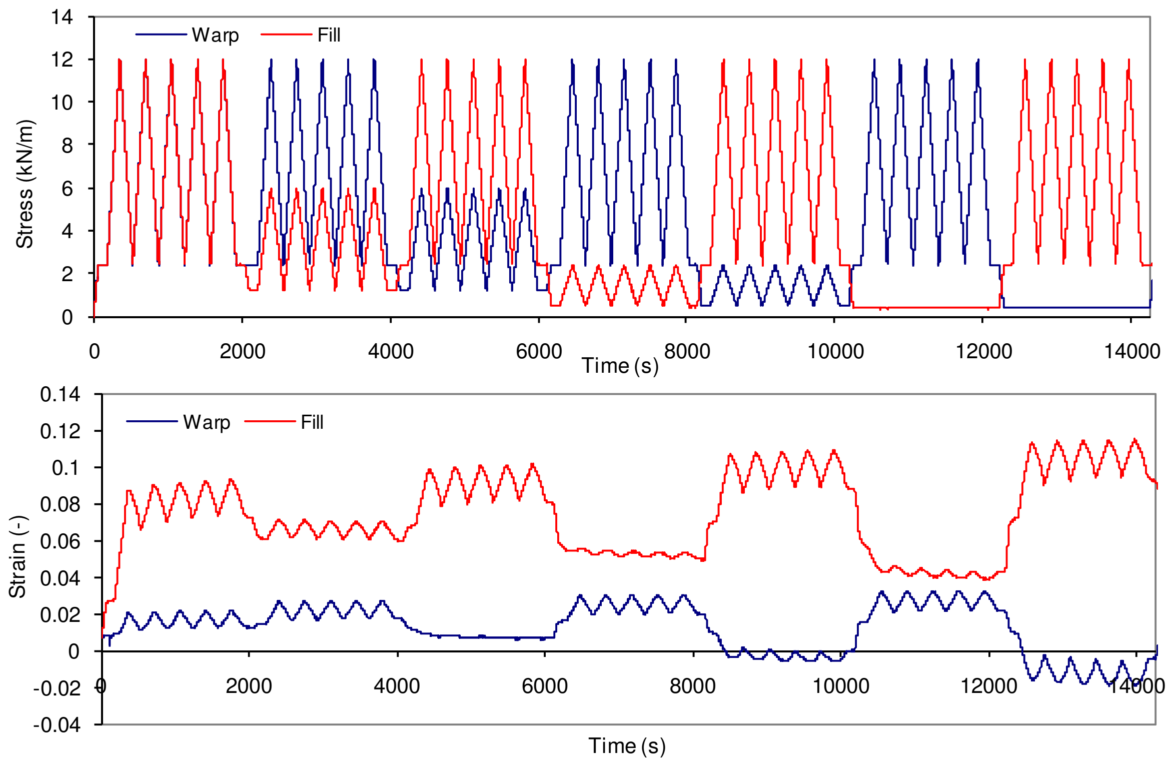

Figure 4: Test protocol used at EMPA: load history and corresponding strain

For the present study, seven load ratios were investigated, namely 1:1, 2:1, 1:2, 5:1, 1:5, 1:0 and 0:1. The corresponding load history and measured strains are presented in Figure 4.

The last loading cycle of each tested load ratio is used for the determination of the material behaviour, which is typically described using a linear elastic orthotropic model or the non-linear model proposed by the authors[7].

3.4 Comparison

The stress-strain curves measured with the 3 test procedures are compared in Figure 5 for a 1:1 load ratio. The presented results are reduced to the same strain interval from 4% to 20% of the UTS. They show that the test protocols produce quite different results, which emphasizes the influence of the test conditions. There is no unique material behaviour but different possible responses. In the next Section the influence of the test parameters is investigated. The objective is to define a domain that would represent all these possible responses.

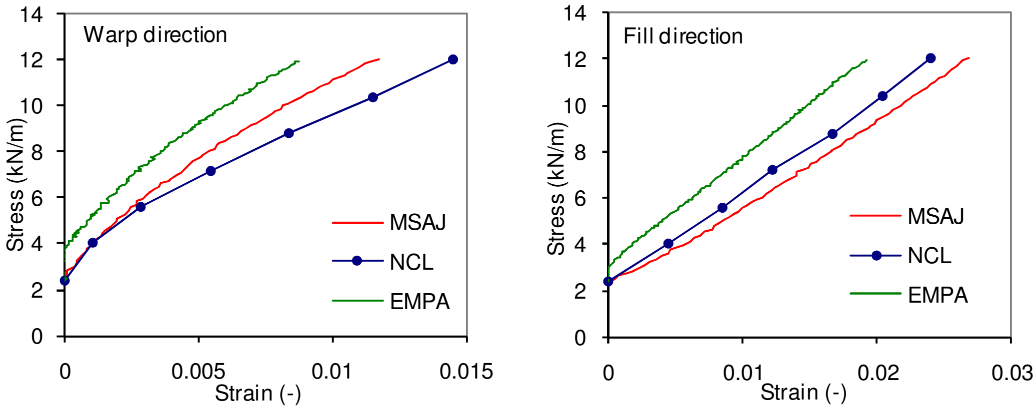

Figure 5: Stress-strain behaviour under 1:1 load ratio: comparison between the test procedures

4 PARAMETERS INFLUENCING THE MATERIAL BEHAVIOUR

4.1 Repetition of load cycles

Repetition of load cycles is used to reduce the level of residual strain. After each cycle more residual strain is removed and therefore the material stiffness is changed. The influence of cycle repetition is illustrated in Figure 6 for a 1:1 load ratio. The slope of the stress-strain curves increases at each new cycle in both warp and fill directions until the fourth and fifth cycles which are very similar. It seems therefore that after several cycles a stabilized solution is obtained.

4.2 Past load history

The past load history plays an important role in the material behaviour. The state of the material (crimp in the yarns, level of residual strains) before a new load cycle depends on the previous loadings. In order to investigate this influence a special test protocol is proposed where cycles of 1:1 load ratios are alternated with cycles of other load ratios: 1:1(A), 2:1, 1:1(B), 1:2, 1:1(C), 5:1, 1:1(D), 1:5, 1:1(E). For each load ratio 5 cycles are applied. The stress-strain curves obtained in the warp direction for the first and last cycle of each series of 1:1 load ratio are presented in Figure 8. Similar results are obtained in the fill direction.

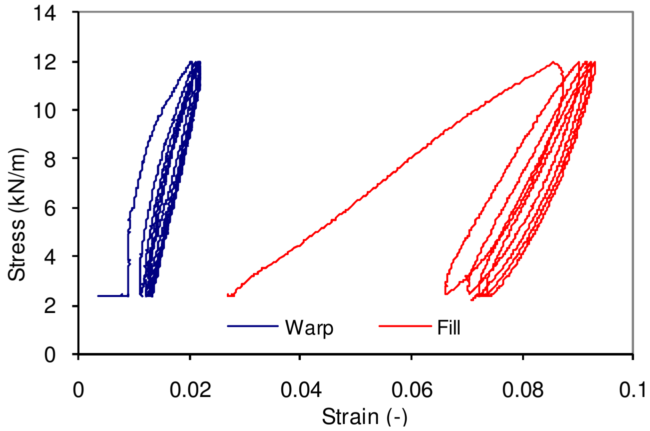

Figure 6: Influence of cycle repetition for a 1:1 load ratio (EMPA test)

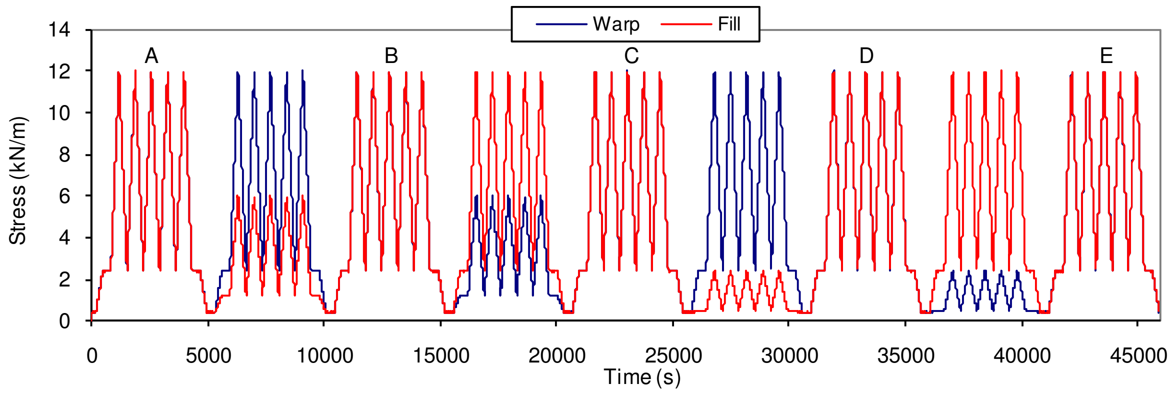

Figure 7: Test protocol used to investigate the influence of the load history

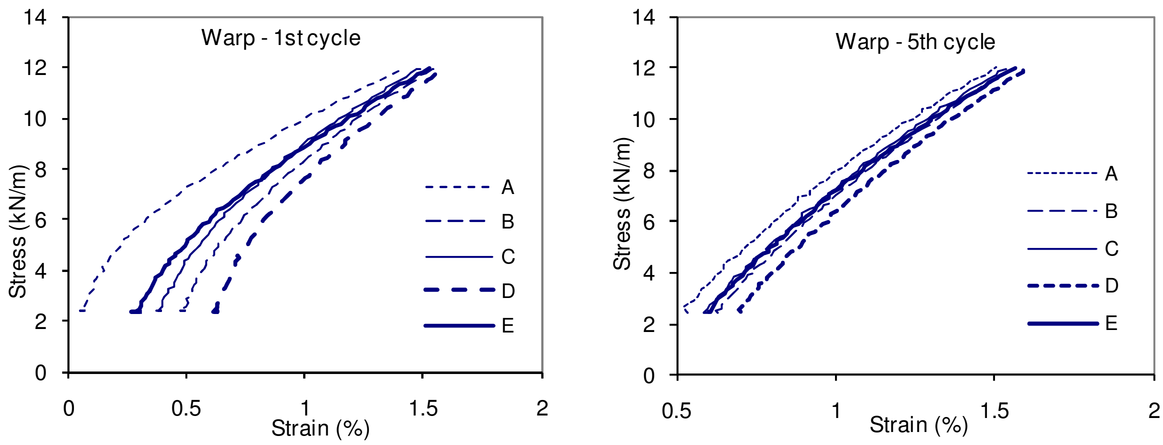

Figure 8: Influence of the load history in the warp direction for a 1:1 load ratio

Results show that the response of the first 1:1 load cycle of each series is strongly influenced by the loading that has been applied just before. The response is softer if before no load was applied (cycles A) or a very high load was applied in the opposite direction (cycles E for warp). On the contrary after 5 cycles there is a much smaller influence of the load history and similar curves are obtained.

4.3 Pre-stress

The pre-stress is the lowest stress level that is permanently applied on the material. Since the pre-stress is a long-term loading it will result in creep of the material. Therefore, the higher the pre-stress is, the more residual strains are removed. This has an influence on the material behaviour in particular during the first load cycles. After repeated cycles most of the residual strains are removed, so that the response does not depend on the initial pre-stress level. In order to investigate this influence two new samples were initially maintained under pre-stress during 6 hours at 4% of UTS and 1.3% of UTS, respectively, and then loaded under 1:1 load ratio. The stress-strain curves determined for this loading are presented in Figure 9. There is very little influence of the pre-stress in the warp direction which is less affected by large residual strains. In the fill direction however, a higher pre-stress gives a response that is initially stiffer.

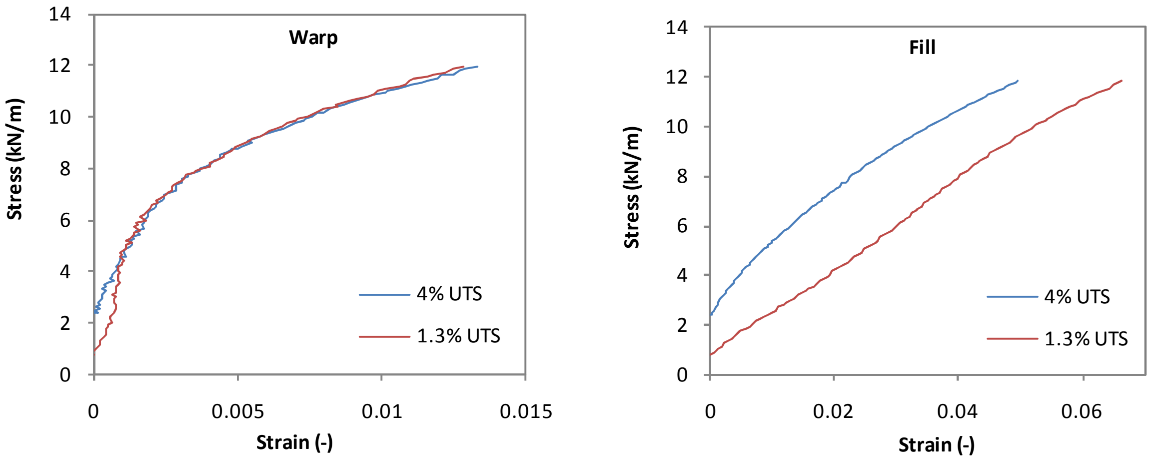

Figure 9: Influence of the initial pre-stress level for a 1:1 loading

4.4 Loading rate

Investigating the influence of the loading rate with a single biaxial test protocol is difficult because one cannot separate the contribution of the loading rate to the contribution of the load history on the results. The only solution is to test a new sample for each strain rate. It was therefore chosen to perform uniaxial tests that require less material. Straps (length 500 mm, width 100 mm) were tested under uniaxial tension up to 50% of the UTS in both warp and fill directions. The tensile uniaxial response is presented in Figure 10 for different loading times corresponding to uniaxial loading rate from 25 to 1000 (N/m)/s. Results show that the material only becomes slightly stiffer at higher rates, so its rate-dependency is quite moderate.

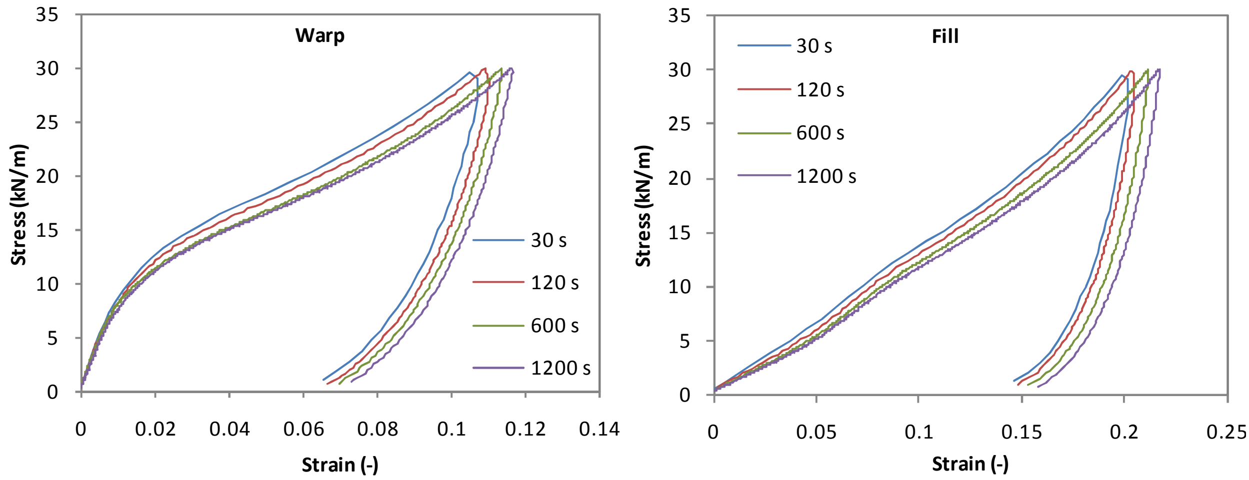

Figure 10: Influence of the loading rate measured with uniaxial tensile tests in warp and fill direction

5 DEFINITION OF A RESPONSE DOMAIN

5.1 Proposed test protocol for the definition of the boundaries

It has been shown in Figure 5 that the behaviour of the material depends on the test conditions. Based on the investigations of Section 4 that have emphasize the influence of each test parameter one can define a response domain that would represent all possible responses of the material.

The definition of a domain requires the determination of boundaries. In that case one would need to define an upper "stiff" limit and a lower "soft" limit.

It has been shown in Figure 6 that after 5 cycles a stabilized response is obtained. Moreover it has been shown in Figure 8 that after 5 cycles the load history has no more influence. Therefore the EMPA test procedure that includes 5 cycles per load ratio can be used for the determination of this upper limit.

The definition of a lower limit is not as straightforward since the material behaviour is affected by the load history. It can be seen from Figure 6 that the first cycle usually exhibits a much softer behaviour compared to the following cycles. This first cycle represents in that case the very first response of the material to a 1:1 load cycle after a short initial pre-stressing. Such initial response emphasizes the initial large strains that occur in a new material. These permanent strains are usually taken into account by means of compensation tests to estimate the final shape of the structure. In order to determine the material initial behaviour it is necessary to test a new sample for each load ratio, which is material- and time-consuming. Moreover, this behaviour only happens once at the very first loading. The following loadings will all show a stiffer behaviour as most of the initial residual strains will have been removed. This definition of an initial response is therefore not the most appropriate to define a lower limit of the material response under operation conditions. The objective of defining such a response domain is indeed to represent the limit of the material behaviour on a real structure. A more appropriate solution would be to measure the response of a sample after it has been initially loaded removing the large initial residual strains. The measurement would then be done based on a unique loading after a period of rest.

A test protocol is proposed that aims at representing the material response on a structure after a period of rest (loaded under pre-stress only). The load history is presented in Figure 11. A new sample is first maintained under pre-stress during 6 hours. Then load cycles are alternatively performed under 1:1, 2:1 and 1:2 load ratios. After each cycle the sample is kept under pre-stress for 1 hour before the next loading. Each series of three load ratios is performed three times. At the end of the protocol additional load cycles can be integrated for the estimation of the upper limit.

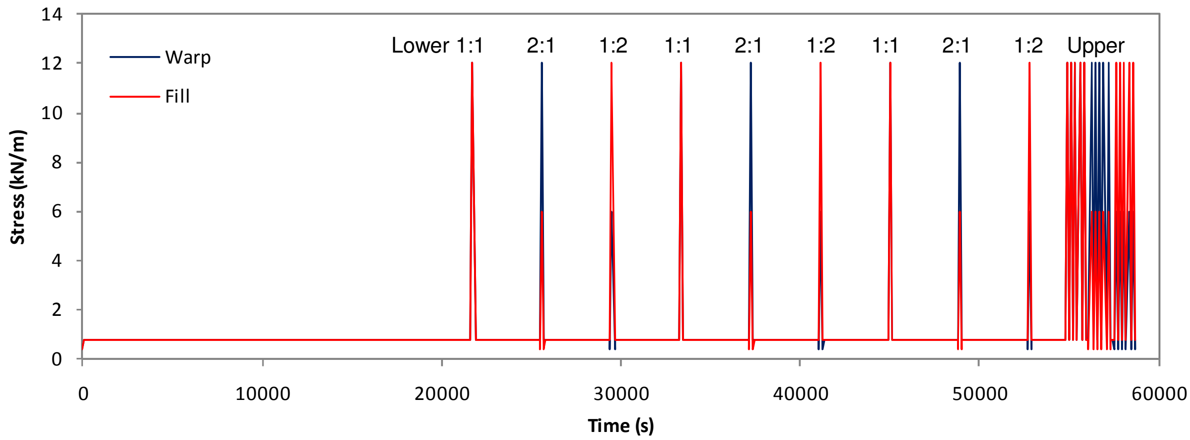

Figure 11: Load history for the determination of the domain boundaries

Results show that the second and third series of loadings give very similar results. The first series appears to be much softer and therefore affected by initial residual strains. As an example the stress-strain curves obtained for a 1:1 load ratio are presented in Figure 12. The lower limit is finally defined as the average of the second and third curves.

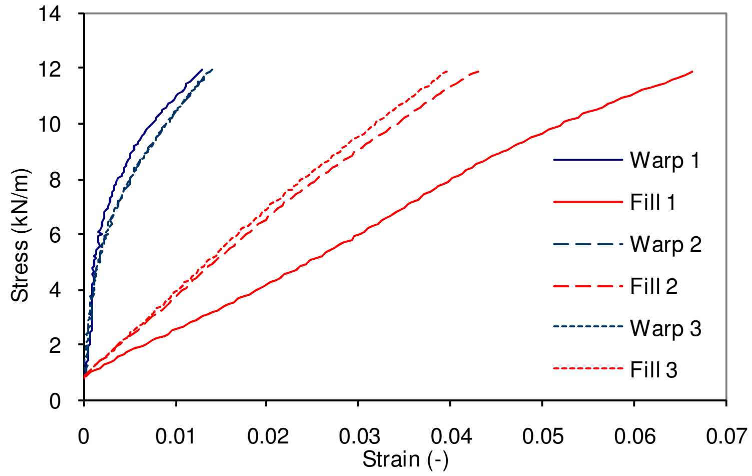

Figure 12: Results obtained on the 3 first cycles of 1:1 load ratio based on the proposed protocol

The influence of the pre-stress and of the loading rate on the proposed test protocol was investigated. Three tests were performed on three new samples using two different pre-stress and different loading times for the measurement of the lower and upper limits. Results of the investigation are presented in Figure 13. As it could have been expected from the observations of Section 4, the pre-stress level does affect the material behaviour while the loading rate has no influence. The upper limit is also not very sensitive to the test parameters.

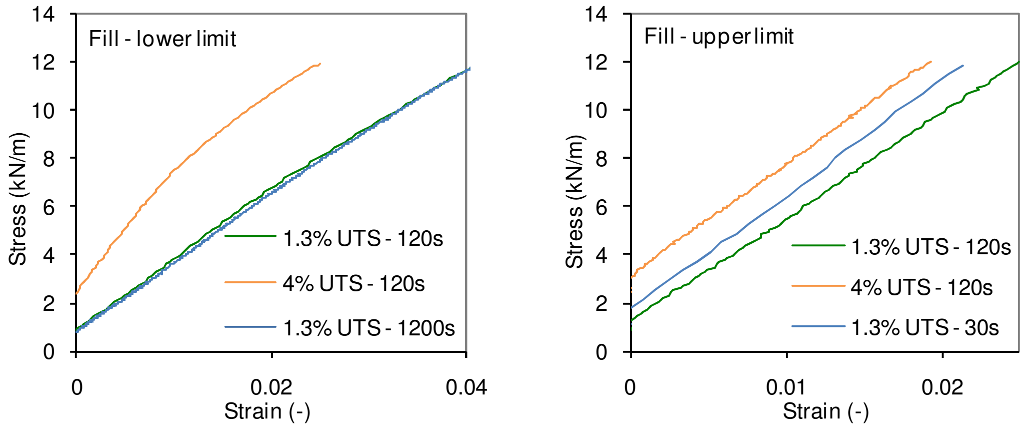

Figure 13: Influence of test parameters on the lower and upper limit in the fill direction

5.2 Comparison between the response domain and the MSAJ and NCL tests

It has been shown that the pre-stress has a significant influence on the material behaviour. In the previous comparison (Figure 5) the pre-stress used for the EMPA procedure was significantly higher than for the two other tests. For this new comparison a pre-stress of 1.3% of the UTS is chosen similarly to the NCL protocol. The parameters of each test are summarized in Table 1.

	MSAJ	NCL	EMPA upper	EMPA lower
Load cycles	3	1 (with steps)	5	1
Past load history	none (new sample)	pre-stressing and conditioning	pre-stressing and 9 load cycles	pre-stressing and 3 load cycles
Pre-stress	0.3% UTS	1.3% UTS	1.3% UTS	1.3% UTS
Loading rate	123.3 (N/m)/s	14 (N/m)/s	93.5 (N/m)/s	93.5 (N/m)/s

Table 1 : Comparison between the test parameters

The final results are presented in Figure 14. Overall, there is a reasonably good match between the NCL test procedure, the MSAJ standard and the response domain defined by EMPA's test protocol if similar pre-stress levels are used. The results obtained with the Japanese standard are indeed always included in the response domain in green. This is presumably due to the similarities between both test procedures. However, it can be emphasized that the behaviour derived from the Japanese standard test is much softer than the upper limit of the domain. This proves the strong influence of the amount of cycles on the material response. It seems that three cycles are not sufficient to completely remove the residual strains and therefore to obtain a converged solution.

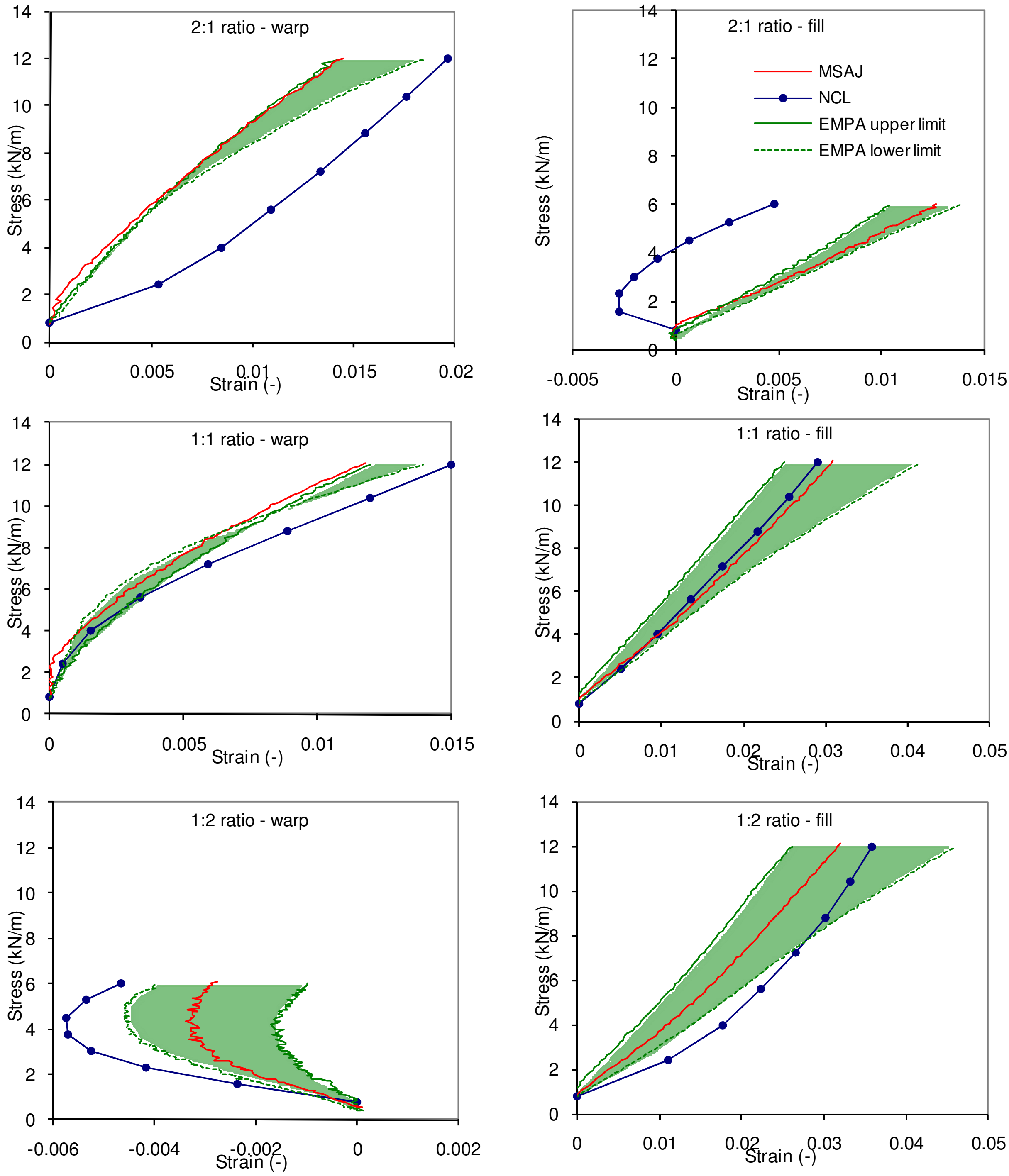

Figure 14: Comparison between the MSAJ standard, the NCL protocol and EMPA's response domain

The lower limit however is not always the softest measured response. In particular in case of a 2:1 load ratio the response measured with the NCL method is much softer. The cause of this difference cannot be related to the pre-stress or to the cycle repetitions that are very similar. The loading rates are different but it has shown very little influence on the results. It must therefore be due to the load history. In fact it can be seen in Figure 3 that prior to the 2:1 load ratio (cycle E) a 0:1 load ratio is applied (cycle A). This can have a significant influence on the stiffness measured in the warp direction under the 2:1 load ratio as it has been explained in Section 4.

6 CONCLUSION

Three test protocols for the investigation of the biaxial response of PVC-coated polyester fabrics have been compared. Results emphasize the significant influence of the test conditions on the material response, in particular the level of pre-stress, the amount of repeated load cycles and the initial material conditioning. It is therefore impossible to assess which method is more appropriate to the investigation of the biaxial mechanical behaviour of coated-fabrics.

A new approach has been proposed that could give a representation of the material behaviour variability and therefore help to define the limits of the possible behaviour of tensile structures. A response domain for the material has been presented whose limits can be experimentally determined. The upper limit would represent the material stiffest solution obtained after several load repetitions. The lower limit would represent the softest material response on a real structure, defined as the response of an initially loaded sample after a period of rest. Any further loading of the fabric is then expected to produce a response that is included within the previously described boundaries if the pre-stress is adjusted in the test procedure to match the design requirements. It has been observed for the studied material that the upper limit could be up to 60% stiffer than the lower limit. Those two limits might be used to calculate two extreme cases of the structure behaviour. If the variability is not so pronounced then an average of both limits might also be used for the material model.

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